



Navigation Accuracy at Jupiter and Saturn Using Optical Observations of Planetary Satellites

AAS 19-231

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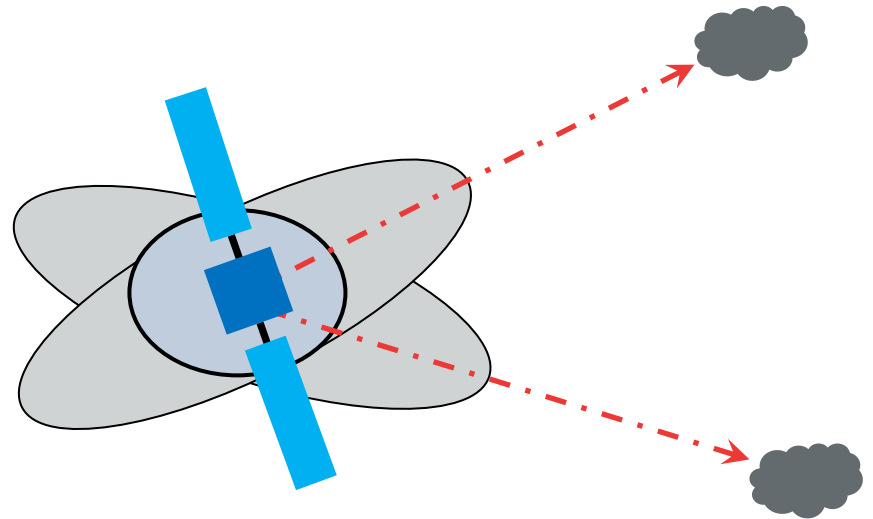
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Introduction

- Standard deep-space navigation relies on radiometric data, obtained using one or more ground-based tracking stations, such as the Deep Space Network (DSN)
- The DSN is a heavily-used resource, and tracking needs are expected to increase in the future
- One way to alleviate this, and to enable new types of missions, is to perform onboard autonomous onboard navigation ("AutoNav")
- AutoNav has been very successful in the limited uses to date
 - Deep Space 1: short interplanetary cruise segment using low thrust, flyby of comet Borrelly
 - Stardust/NEXT: flybys of asteroid Annefrank, and comets Wild 2 and Tempel 1
 - Deep Impact/EPOXI: impact and flyby of Tempel 1, flyby of comet Hartley 2
- AutoNav thus far has relied solely on onboard optical measurements, making the system entirely self-contained
- Our goal is to analyze the capability of a purely optical system to perform navigation for a wide variety of scenarios
 - Previously: What is the expected accuracy for cruise navigation? (AAS 17-599)
 - Today: **What is the expected performance for missions to Jupiter and Saturn?**

AutoNav Concept

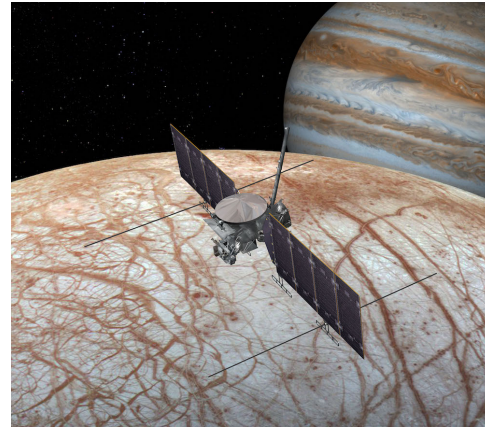
- A spacecraft can triangulate its position on-board using images of targets (asteroids, moons, planets, other objects)
- We can compute an instantaneous *kinematic* position uncertainty
- Observations can also be *filtered* to take advantage of correlated time-varying observations



***During approach and orbit around Jupiter and Saturn,
can we navigate accurately enough using only images of
the planets' moons?***

Scenarios Investigated

- Deep-space cruise
 - AAS 17-599 paper
- Jupiter approach
 - Juno
 - Europa Clipper
- Jupiter tour
 - Europa Clipper
- Saturn tour
 - Cassini



Model Assumptions

- Optical images of natural bodies sole data type
- Imaging targets included:
 - Jupiter: Io, Europa, Ganymede, Callisto
 - Saturn: Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus, Phoebe
 - Note: Titan is excluded due to likely center-finding difficulties with its atmosphere, and close flybys in the Cassini trajectory
 - Other moons are too small and dim to be reliably imaged

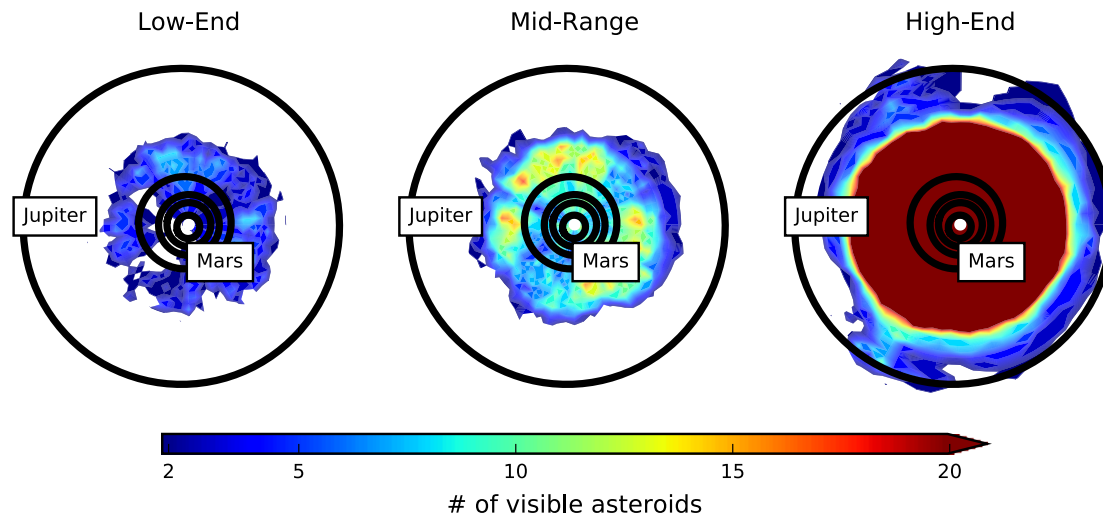
- Four cameras modeled, 0.5-pixel data weight (1-sigma)

Name	FOV (deg)	Θ (μ rad)	M_{max}	ψ_{min} (deg)
Low Res	26.9	128.0	9.5	30
Mid Res	7.0	60.0	10.5	30
Hi Res	0.6	10.0	13.5	30
Cassini NAC	0.35	6.0	14.0	30

- Targets are excluded if too dim, or if within 5% FOV from planet's limb, or if transiting/occulted by planet

Cruise

- Previous results using asteroid targets showed that it is *challenging* to rely solely on AutoNav to navigate beyond the asteroid belt



- But there are workarounds
 - TCMs are often performed in the inner solar system, when there are many visible targets
 - Spacecraft hibernation until approach to outer planet destination
 - “Dead-reckoning” navigation during hibernation or long period with no observations
 - Use sparse, selectively-chosen radiometric tracking

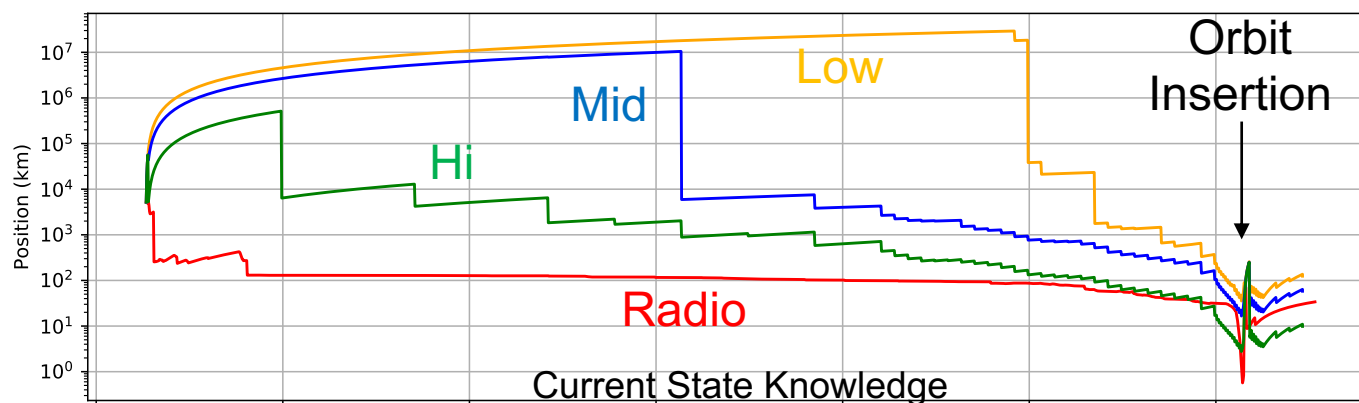
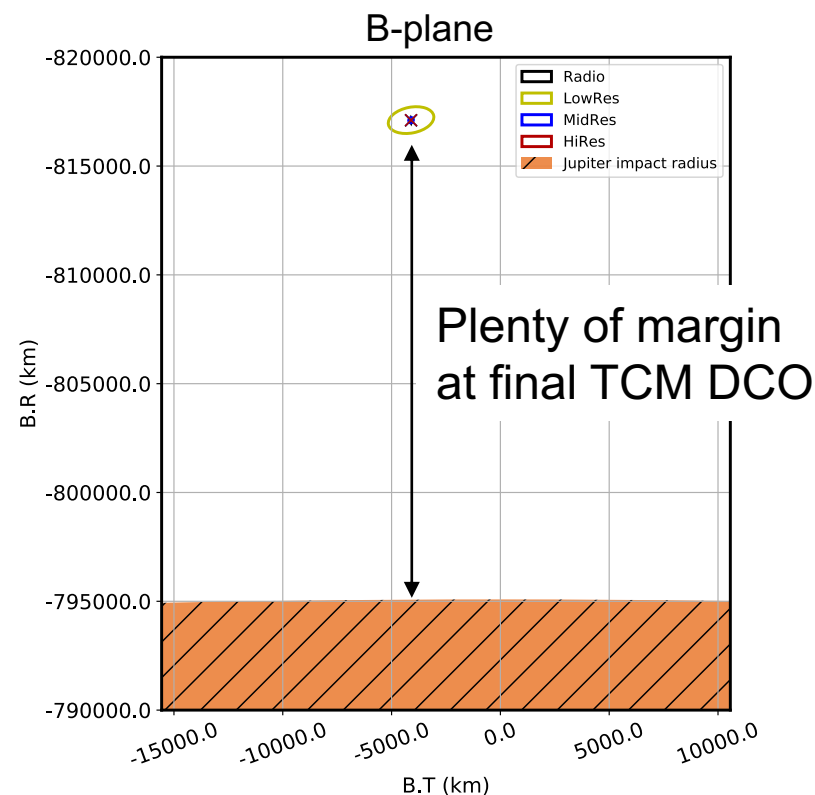
Planetary Approach

- Currently have analyzed planetary approach for Jupiter using two scenarios, Juno and Europa Clipper
- All results assumed optical only data of the natural satellites
- Results use spacecraft models as flown (Juno) and planned (Europa Clipper)
- Results analyzed in terms of orbit determination uncertainties using a full navigation filter, and DV99 statistics
 - DV99 is a Monte Carlo sampling method to analyze fuel required, at the 99% confidence level, to achieve mission goals

Jupiter Approach – Juno

Image time (2016, ET)	Low Res				Mid Res				Hi Res			
	I	E	G	C	I	E	G	C	I	E	G	C
13-APR 21:00								✓		✓	✓	✓
23-APR 21:00									✓	✓	✓	✓
03-MAY 21:00									✓	✓	✓	✓
13-MAY 21:00								✓		✓	✓	✓
18-MAY 21:00									✓	✓	✓	✓
23-MAY 21:00							✓	✓	✓	✓	✓	✓
28-MAY 21:00									✓	✓	✓	✓
02-JUN 21:00							✓	✓	✓	✓	✓	✓
07-JUN 21:00							✓	✓	✓	✓	✓	✓
08-JUN 21:00							✓	✓	✓	✓	✓	✓
09-JUN 21:00							✓	✓	✓	✓	✓	✓
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
04-JUL 01:00	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
04-JUL 05:00			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
04-JUL 09:00	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
04-JUL 13:00	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
04-JUL 17:00	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
04-JUL 21:00	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Image schedule



Jupiter Approach – Juno

ΔV_{99} analysis: statistical sampling method to determine fuel needed to achieve mission goals.

Here, analyzed for orbit insertion maneuvers and compared with standard radiometric navigation results :

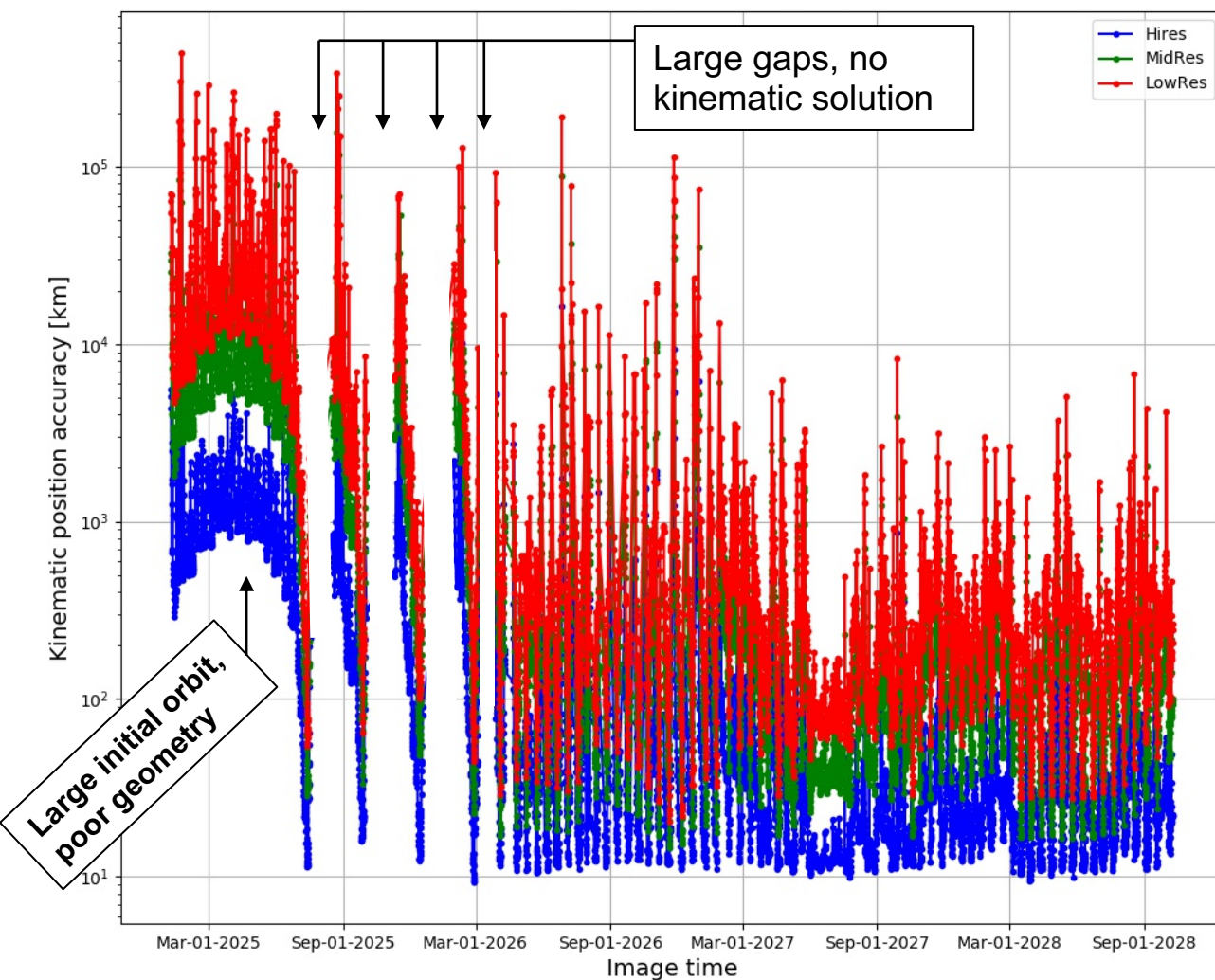
Name	Time (2016, ET)	Nom. Mag. (m/s)	Maneuver ΔV_{99} (m/s)			
			Radio-only	Low Res*	Mid Res	Hi Res
TCM-12	31-MAY 18:00:00	0	1.607	—	4.611	1.619
TCM-13	20-JUN 18:00:00	0	10.671	—	58.053	13.490
JOI**	5-JUL 02:31:08	542.1086	—	—	—	—
JOI-CLN	13-JUL 18:00:00	0	23.766	—	132.521	36.613
Total***			30.806	—	190.360	47.189

- Juno approach conclusions:
 - All cameras can safely avoid Jupiter impact by the final TCM
 - Low Res camera cannot see sufficient targets at penultimate TCM
 - **Feasible with Mid- or Hi-Res Camera** ✓
- Europa Clipper results are similar, but not shown in this presentation

Outer Planet Tours

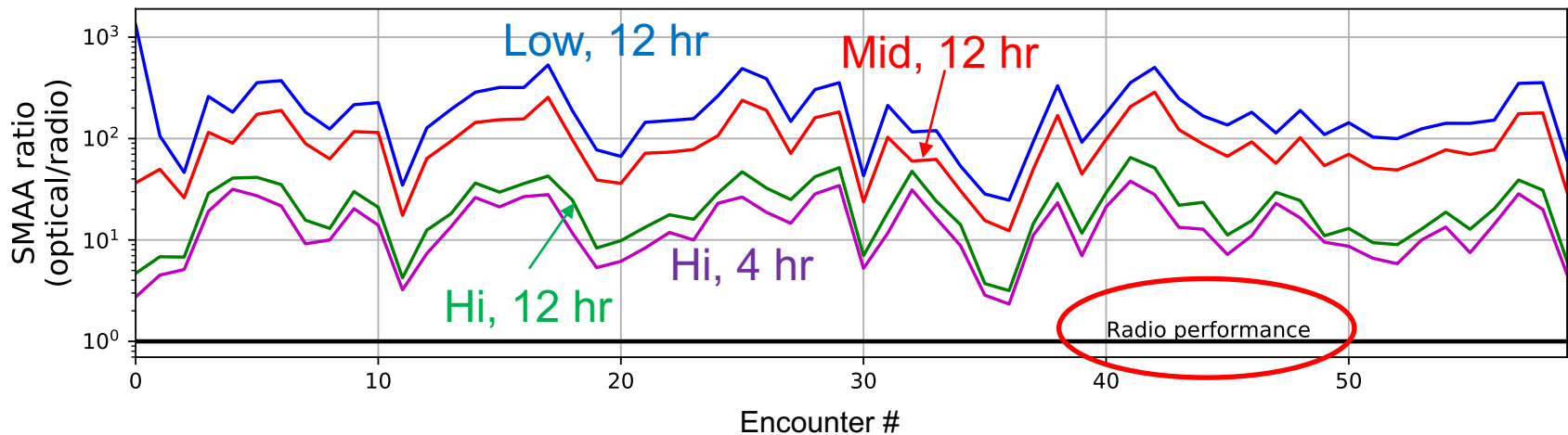
- Long duration (14+ years for Cassini, for example), with multiple flybys of satellites required intensive ground operations with large navigation teams
- Question we wanted to answer: can such a tour be done using only optical data, thus enabling a fully autonomous tour?
- We first looked just at generic kinematic results to get an idea of overall accuracy floor for the Jovian and Saturnian systems
- We then specifically analyzed the entire Europa Clipper tour using a full navigation filter and the DV99 statistics
- We also analyzed a single arc of Cassini to compare against ground-based navigation results

Jupiter Tour – Europa Clipper, kinematic



- Kinematic position uncertainty along Europa Clipper trajectory, every 4 hours
- Uncertainty varies from ~ 10 km to >1000 km, higher during pump-down orbits
- Large gaps where no kinematic solution is found (<2 targets satisfy criteria)

Jupiter Tour – Europa Clipper, filtered



- AutoNav observables simulated through entire Europa Clipper tour
- B-plane results compared to radio-only solution
- AutoNav is *consistently worse* than radio-only, even by a factor of 100x

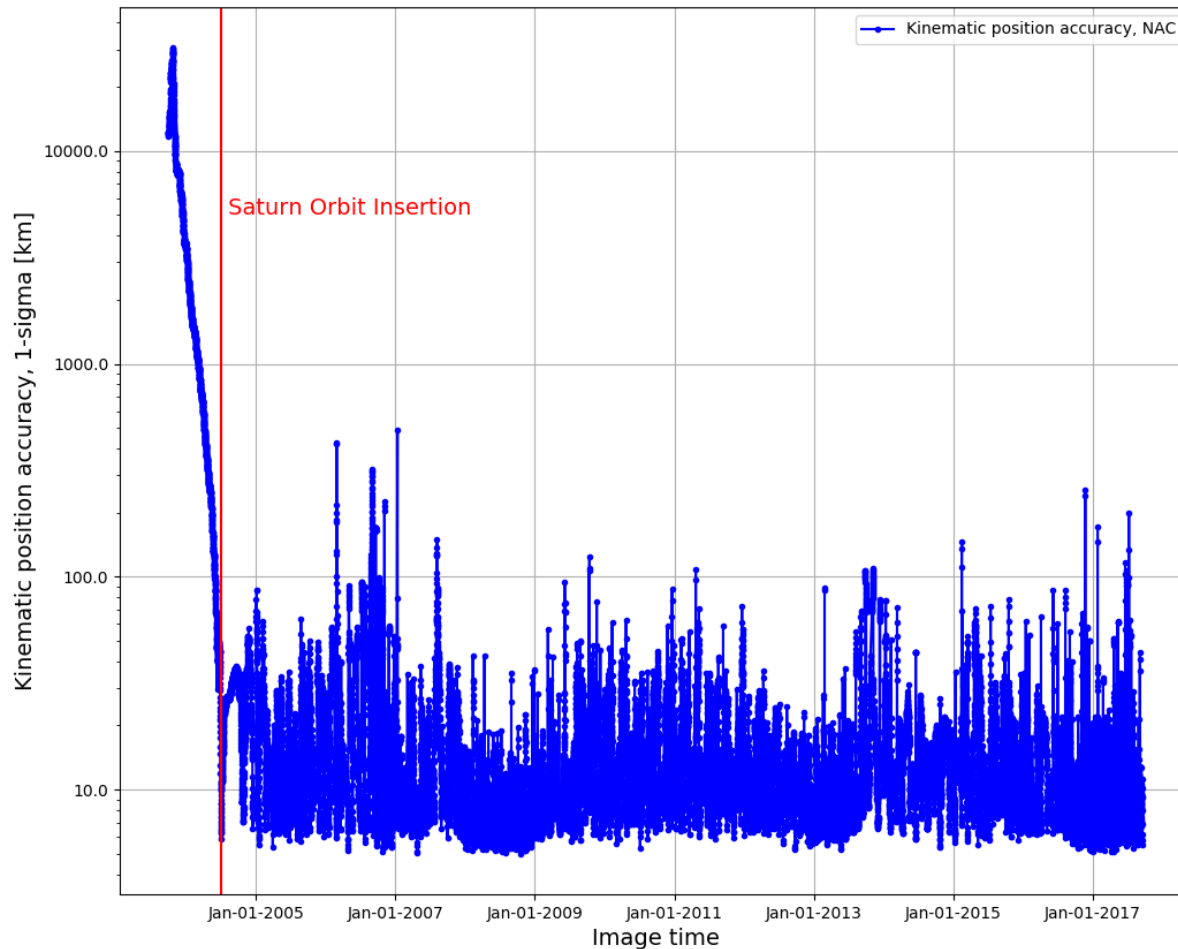
Jupiter Tour – Europa Clipper, filtered

ΔV_{99} analysis for entire tour:

Case	Image frequency	ΔV_{99} (m/s)
Radio-only	—	448.03
Low Res	12 hr.	35645.56
Mid Res	12 hr.	32162.84
Hi Res	12 hr.	919.58
Hi Res	4 hr.	734.21

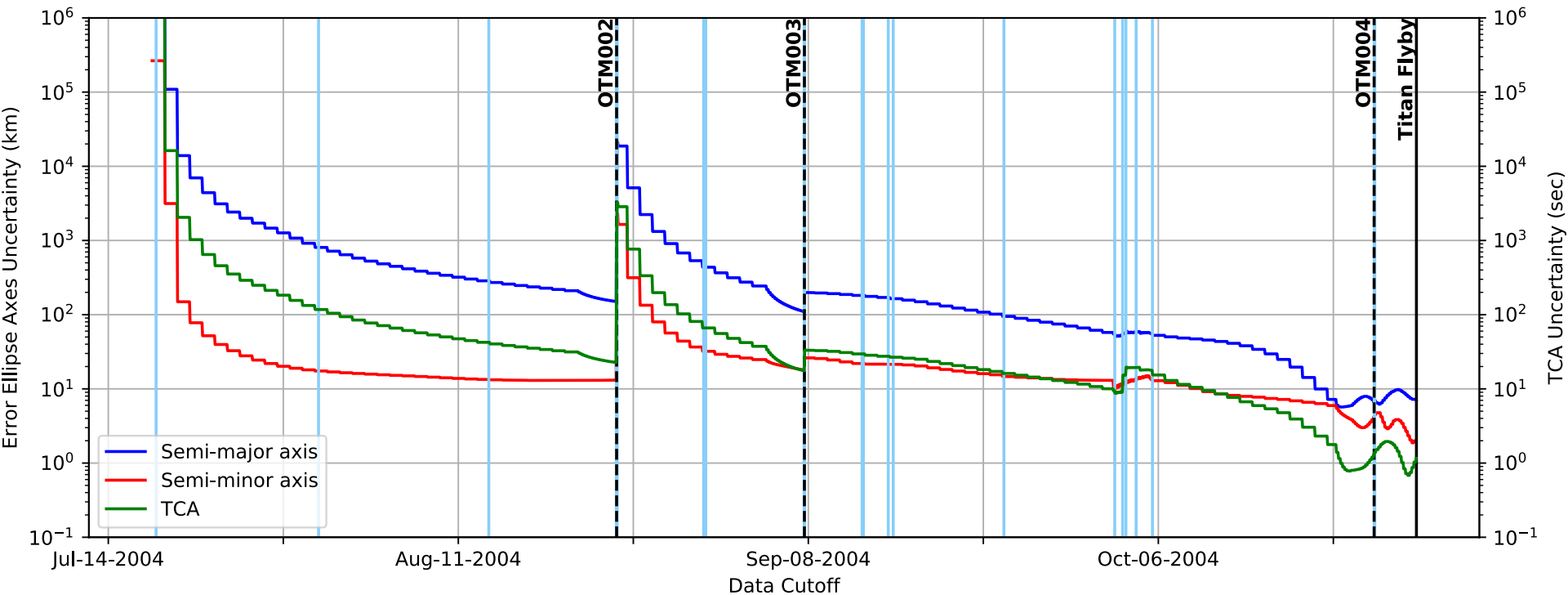
- Europa Clipper tour conclusions:
 - Only Hi-Res camera has a ΔV_{99} that is anywhere near reasonable
 - All cameras have worse B-plane performance than radio-only
 - Very low flybys (some at 25 km altitude) present a demanding navigation challenge
 - Solution may benefit greatly from sparse radio data
 - Barely possible for Hi-Res Camera, but image cadence is not feasible **X**

Saturn Tour – Cassini, kinematic



- Kinematic position uncertainty along Cassini trajectory, every 4 hours
- Uncertainty after SOI is consistently 10-100 km or better
- No large gaps, meaning >2 targets visible at all times

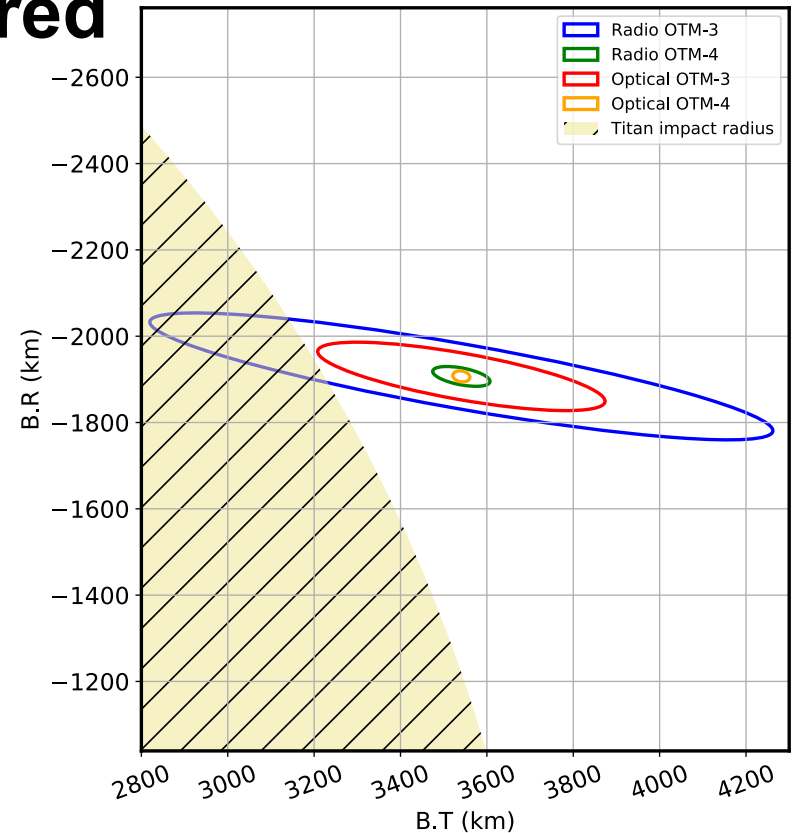
Saturn tour – Cassini, filtered



- Filtered results for a single Titan-Titan arc using only optical targets (NAC)
- Arc has 3 maneuvers (“OTMs”) to target the subsequent flyby
- Plot shows that B-plane uncertainty improves significantly over time and is quite reasonable at the time of the final maneuver (OTM-004)

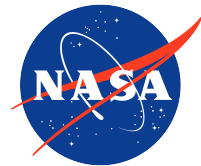
Saturn tour – Cassini, filtered

- B-plane for final two approach maneuvers, optical vs radio
- Optical *outperforms* the radio results from the as-flown mission
- Cassini tour conclusions:
 - The NAC performs very well, better than radio!
 - Only one arc was analyzed, but the consistency of the kinematic solution suggests that these results may be applicable to other arcs
 - Feasible with the NAC flown by Cassini ✓



Conclusions

- Cruise to the gas giants requires alternate strategy (hibernation, radio nav, etc.)
- Approach and insertion at the gas giants is feasible with a mid-level camera or better ✓
- The Europa Clipper tour at Jupiter is difficult or impossible with AutoNav-only, due to the low number of visible targets at Jupiter and the poor geometry ✗
- The Cassini tour at Saturn is a very promising candidate for AutoNav-only, due to the high number of visible targets and favorable geometry ✓
- Next steps: ice giants, cislunar space, strategic addition of radiometric data

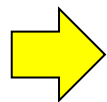
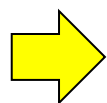


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Backup

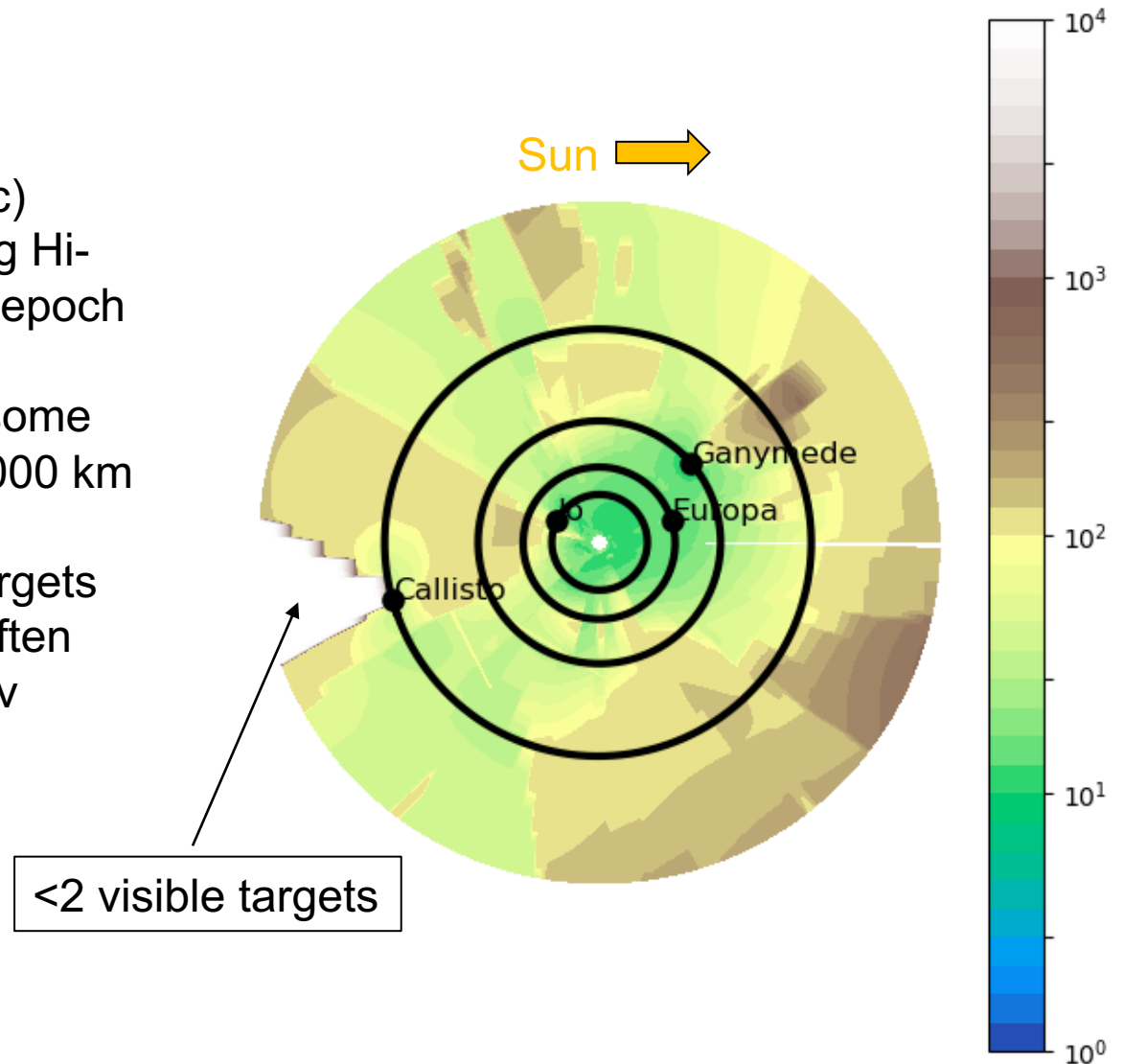
Measurement Error Sources



Error Source	Magnitude	We use	Comment
Center-finding: Point source	0.1 – 0.25 pixel	0.25 pixel	Primary source of error for distant targets
Center-finding: Extended Body	0.25 – 0.5 pixel	Point sources assumed here	Accuracies are good for targets with no atmosphere. New methods are being explored to improve this accuracy.
Target ephemeris uncertainty	10s of km	Latest formal covariance	Formal uncertainties provided by JPL Solar System Dynamics group
Camera pointing	< 3 urad	0 urad	Can be solved for [precisely] assuming at least 3 stars can be seen in image
Camera mounting	-	0 urad	Only matters if relying upon camera pointing estimate from star trackers
Focal length	< 0.1 %	0%	Minimized with an in-flight calibration campaign
Distortion	< 0.1 pixel	0	Minimized with an in-flight calibration campaign
Spacecraft clock errors	< 1 sec	0	Clock drift accumulates during autonomous operations; Could result in errors up to ~20 km, but this is negligible for deep space cruise applications. Could also assume infrequent communications to update on-board clock

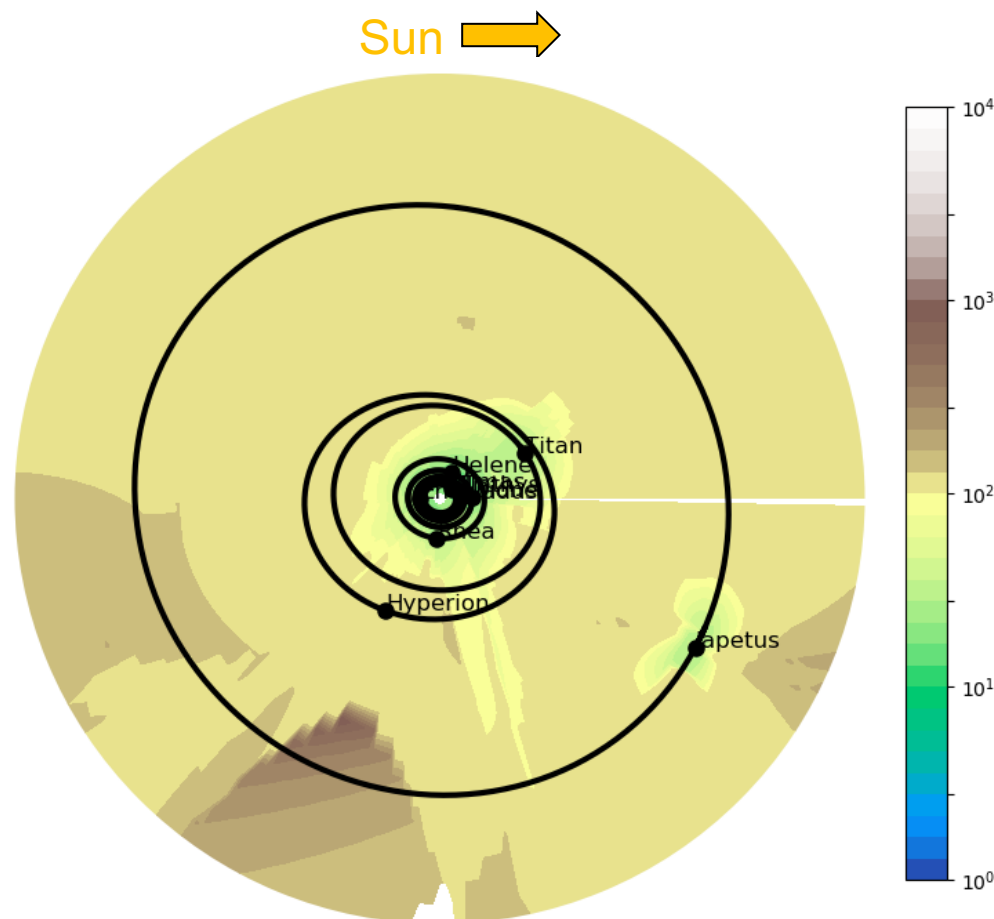
Jupiter Tour – Kinematic

- Instantaneous (kinematic) position uncertainty using Hi-Res camera at a certain epoch
- Performance is patchy, some areas <10 km, some >1000 km
- Low number of visible targets (4) means geometry is often not favorable for AutoNav

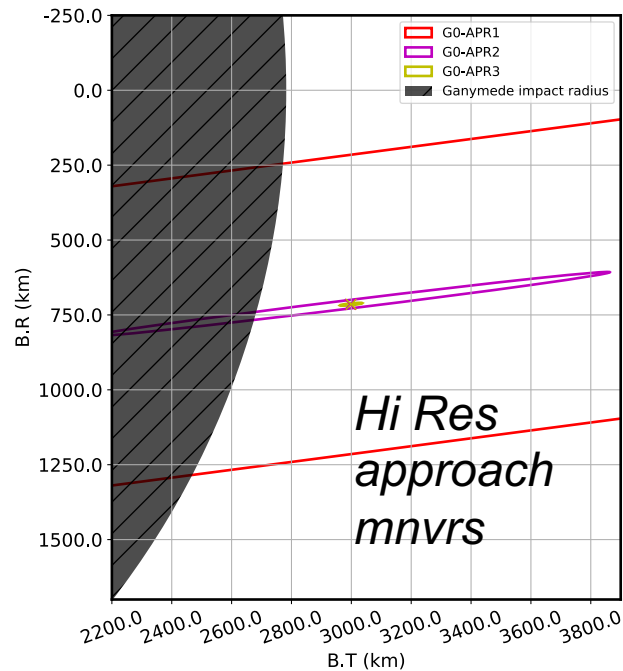
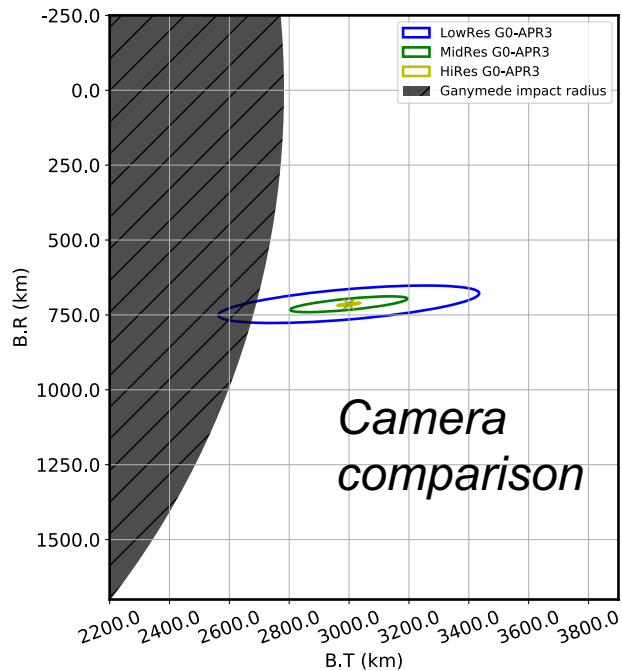
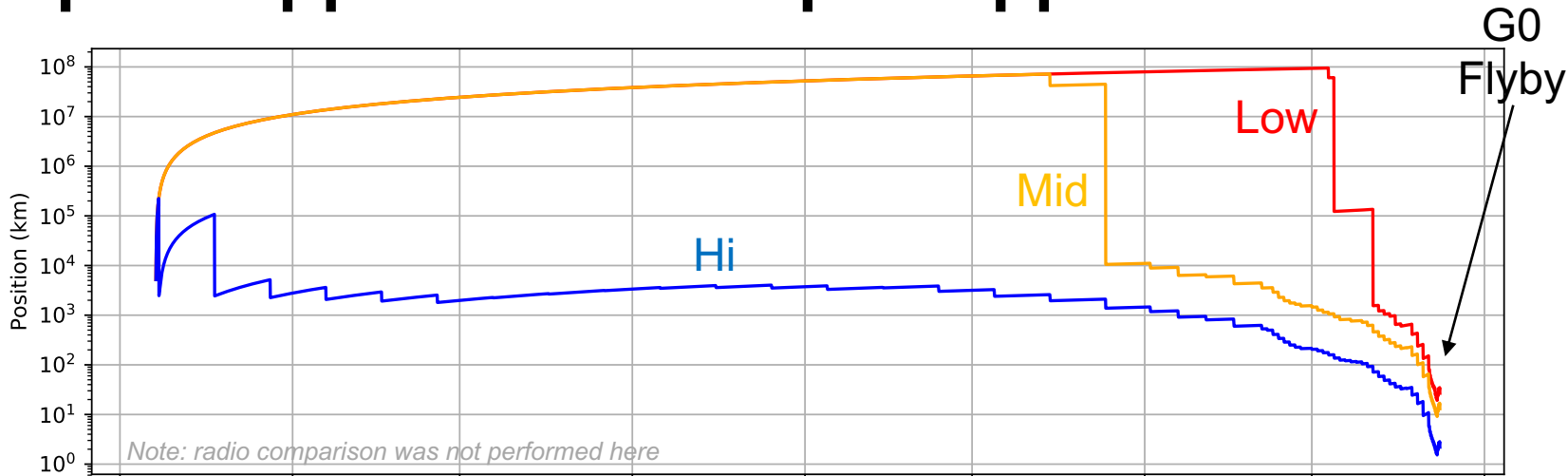


Saturn Tour – Kinematic

- Instantaneous (kinematic) position uncertainty using Hi-Res camera at a certain epoch
- Performance is consistent, ~10 km close to Saturn, ~100 km elsewhere
- Higher number of visible targets (8) and larger elongation of moons means that geometry is almost always amenable to AutoNav



Jupiter Approach – Europa Clipper



Jupiter Approach – Europa Clipper

- Europa Clipper approach conclusions:
 - Mid- and Hi-res can safely avoid Ganymede impact by the final TCM
 - Low Res camera cannot see sufficient targets at first two approach TCM data cutoffs
 - Feasible with Mid- or Hi-Res Camera ✓